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MECHANICS OF SOLIDS AT THE SIBERIAN DIVISION OF THE RUSSIAN ACADEMY OF SCIENCES IN 1988–1997

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The present review of the theoretical and experimental studies in mechanics of solids performed at the scientific centers in Novosibirsk, Krasnoyarsk, Tomsk, and Yakutsk in the last decade is a continuation of the review of the investigations performed at the Siberian Division of the Russian Academy of Sciences from 1957 till 1987 [1].

1. Mathematical Models of Solids [2–53]. The methods of the mechanics of solids provide the background to engineering computations in modern machine building. The behavior of materials under extreme conditions (intense force and temperature loads, plastic metal working, etc.) is accompanied by considerable plastic deformations. Therefore, the construction of mathematical models of solids, including the investigation of irreversible deformations and failure processes, is one of the basic lines of research in mechanics of solids.

(A) Many experiments on complex loading of various metals and alloys at $t = 20$°C were performed at the Mining Institute (Novosibirsk) [2–5] in the last decade. The laws of elastoplastic deformation under complex loading, i.e., under partial unloading in some directions and under active loading in others, were studied. The possibility of considerable increase in the strength and deformation properties in one or several directions under definite loading conditions was revealed. Figure 1 (x and y are the circumferential and axial stresses of a thin-walled tube, respectively) shows the loading trajectory along which the strength and deformation properties of the initially anisotropic alloy É-110 (Zr and 1% Nb) are increased, and Fig. 2 shows the axial stress (x axis) versus the axial deformation (y axis) for purely axial tension (squares) and complex loading (circles). As is seen from Fig. 2, the yield point σ_{s*} in the axial direction exceeds the initial value of σ_s by a factor of 1.8 and the initial strength limit of the alloy upon axial tension by a factor of 1.2. When the limiting properties are preserved in the circumferential direction, ultimate deformation is increased in the axial direction. Complex loading with partial unloading in some directions and with active loading in others is used as the method of increasing the strength and deformation characteristics of metals and is applied in the manufacture of tubes for heat-liberating members of atomic reactors. This method was granted a patent of the Russian Federation. Zhigalkin et al. [2], Chanyshev [6, 7], and Kovrizhnykh [8] constructed new variants of the relationship between the stress tensor increment $\Delta\sigma_{ij}$ and the strain tensor increment $\Delta\varepsilon_{ij}$ of a strengthening body of the form[1]

$$\Delta\varepsilon_{ij} = C_{ijkl}\Delta\sigma_{kl}.$$

Here the tensor C_{ijkl} depends on instantaneous values of the stresses and strains, the deformation history, and on the direction of subsequent loading, i.e., on the direction of the $\Delta\sigma_{ij}$ vector in the space σ_{ij}.

At the Institute of Physicotechnical Problems of the North (Yakutsk), experimental investigations in which the appearance of plastic strains (deviation from the laws of elastic deformation) was established by highly accurate holographic interferometry and Moiré fringe methods were performed [9, 10]. The gradient

[1]Summation from 1 to 3 is performed over repeat subscripts..

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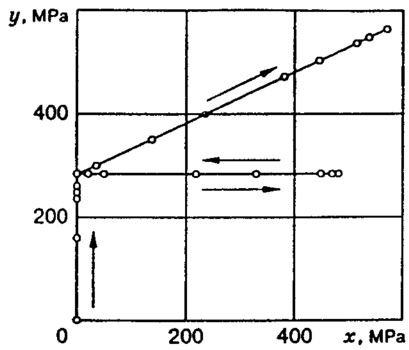

Fig. 1

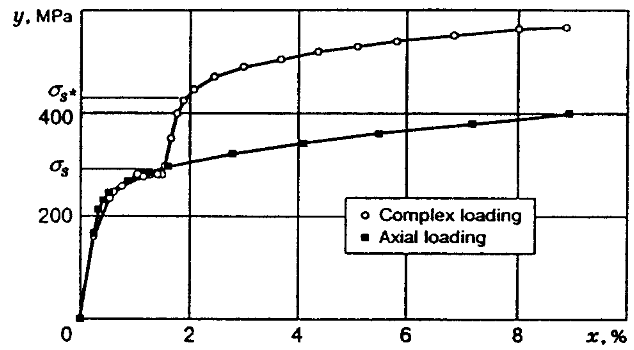

Fig. 2

plasticity criterion of materials in a nonuniform stress state in the form[2]

$$\sigma'_{ij}\sigma'_{ij} = 2k^2\left(1 + \sqrt{L|\mathrm{grad}(\sigma'_{ij}\sigma'_{ij})|}\right)^2$$

was based on the experimental data obtained. Here σ'_{ij} are the components of the stress deviator tensor, k is the shear yield point in a uniform stress state, and L is a parameter that has the dimension of length and depends on the properties of the material (for example, for steel and aluminum alloys, L is of the order of 10^{-1} mm). The range of application of the gradient yield criterion was studied by Legan [11]. In [10, 12], Novopashin et al. analyzed the kinetics of elastoplastic strain with the use of this criterion. For brittle materials, the gradient strength criteria was studied by Legan et al. [13–16].

At the Institute of Strength Physics and Materials Science (Tomsk), based on the experimental data on displacements of the points upon deformation, obtained by the method of laser speckle interferometry, Panin et al. [17, 18] studied the effects of strain localization.

At the Lavrent'ev Institute of Hydrodynamics (Novosibirsk), the formation of localization bands under dynamic loading of various materials (Cu, Nb, Al, Teflon, etc.) was investigated [19, 20]. It was noted that materials undergo forced structuring at the macrolevel. Kostyukov [21, 22] revealed the solid-phase delamination and formation of large-scale structural inhomogeneities in compaction for binary powdered materials.

In [18, 23], Panin et al. developed new continuum models with defects and applied them to the development of methods of computer-assisted synthesis of new materials [24].

In [25], Ivanov and Kurguzov proposed a method of numerical simulation of plane elastoplastic deformation of thin seams between rigid units in which, by the seam, a layer of momentumless finite elements was meant. Equations that determine the forces applied to the edges of the elements versus the average values of the velocities of these edges were derived. In [26], they presented the results of a numerical simulation of displacement waves and deformation localization for a tensile-stressed band of rigid (nondeformable) units with elastoplastic seams whose angles of inclination relative to the axis of the band are of a random character. From the numerical experiments performed, they concluded that knowledge of the displacement waves and rotation of the units at the stages of elastic and initial elastoplastic strains allow one to predict strain-localization zones in a limiting state.

For a long time, continuum models have been advanced independently of the ideas of microstructural mechanisms of irreversible processes in condensed media. At present, these ideas are applied widely for construction of the models of real media. In this connection, the problem of transition from microstructural to macrostructural characteristics arises. To solve this problem, Merzhievskii et al. [27–33] used the Maxwell approach to represent an irreversible deformation of any condensed medium as a macroscopic result of the regrouping and displacement of the molecules (particles) of the medium to a stable equilibrium position. The

[2]See footnote No. 1.

characteristic time of regrouping is a relaxation time of the state parameters. A transition from microstructural to macrostructural characteristics was realized by relating the relaxation time to the macrostructural mechanism (the ideas of the latter may change and develop). This approach made it possible to construct a number of models of dynamic deformation of structurally nonuniform media, including macroisotropic and initially anisotropic ones. Among them are the deformation and fracture models for metals, the model of nonlinear heat conduction which incorporates the finite heat-transfer velocity, and the models of reinforced composites and porous media.

(B) In [34–43], the results of theoretical and experimental investigations of deformation of bulk media and rocks were reported. In [34], Bobryakov et al. presented new experimental data on the specific features of deformation of a bulk medium, and Leont'ev and Nazarov [35] gave the results of model experiments on determination of the tangential rigidity between interblock contacts with the use of mechanical and acoustic data. The effect of the structure on the strength of rocks was discussed by Revuzhenko et al. [36].

The elastoplastic behavior and fracture of materials was described by Shemyakin [37] within the framework of the phenomenological model. This model is based on the idea of the medium as an ensemble of elastic units whose surfaces interact with each other. Residual strain appears owing to the slipping of the units, and considerable slippages lead to failure.

In [38], Revuzhenko treated the rock as a composite with an internal structure. He introduced microvelocity and microstress fields and also determined averaging procedures that allow one to make a transition to the model macroparameters. The problems of the formation of a unit structure upon shear of a loose material were studied in [39].

The asymmetric solution of the equilibrium problem of a plastic mass in a convergent symmetric channel was obtained by the method of peak loading by Babakov and Volodina [41]. An upper estimate of the peak load was found, and the dimensions of fragments into which the plastic medium is fractured in the channel were determined. In [42], Babakov et al. analyzed the action of a flat rigid smooth punch undergoing a transverse load on the inelastoplastic incompressible ground. They described the experimentally obtained pattern of hinged revolution of the ground around the lower end of a punch, derived a formula for the upper estimate of an ultimate load, and made comparison with experiment. The problem of a spherical stress wave in rock bodies was solved by the method of short and weak waves, and the effect of the reinforcement, dilatancy, and internal friction on the propagation of stress waves in solids was evaluated based on this solution by Babakov and Zagorskikh [43].

(C) Experimental and theoretical investigations concerning the determination of the dependence between stress tensors and creep strain velocities were carried out. In terms of the mechanics of solids, a link between high-temperature creep and superplasticity was established in the papers of Tsvelodub, Nikitenko, Sosnin, et al. [44–48]. Some specific features of a high-temperature strain were revealed. The specific features obtained were used to solve the problem of plastic treatment of materials, including superplasticity or related regimes. Some developments have found application in industry [49–53].

2. Mechanics of Composites [54–80]. The stress-strain states of shells made of composites were analyzed in [54–58]. The stability of cylindrical composite shells under static and dynamic loading was studied as well. In [54–56], Nemirovskii et al. clarified the specific features of the supercritical behavior of layered shells, depending on the rigidity characteristics of layers, their mutual positions, wave formation, and on the types of loading. In [57], Andreev and Nemirovskii proposed and realized a numerical algorithm for solving the equations of layered rotational shells, taking into account transverse shears. In [58], Mezentsev and Nemirovskii derived equations to determine stress-strain states of helicoidal shells with allowance for transverse shears and the reinforcing structure. They also presented the scheme of rational reinforcement for the cases of loading at normal pressure.

The problems of design and strength calculation of promising light-weight composite materials which are polymer matrices with inserted spherical microparticles were dealt with in [59–61]. The optimization problem of a layered sphere located inside the matrix upon triaxial tension at infinity was considered by Alekhin and Baev [62]. The order and thickness of the layers from a given set of materials were found for the lightest sphere and its maximum strength.

In [63], models describing the interaction of the components of a fibrous composite during its formation were developed. The conditions for obtaining anisotropic composite materials with maximum reinforcement were determined. The possibilities of creating materials with unique properties were shown using the example of titanium alloys reinforced by high-strength metallic fibers.

The behavior of unidirectional fibrous composites within the framework of a shear model was studied by Mikhailov and Lankina [64, 65]. This model was obtained as a certain asymptotics of the exact formulation of the problem. A method of obtaining more and more exact approximations was given by Mikhailov [66].

The papers by Demeshkin, Kornev, Gorshkov, Makarov, and Aseev [67–72] were devoted to analysis of dynamic deformation and fracture of unidirectional composites. Three (one shock and two explosive) techniques for finding the dynamic characteristics of glass- and organoplastics over a wide range of strain velocities (from quasi-static to rigid explosive loading) were realized. A sharp increase in strength characteristics under shock and explosive loading was established. The time of fracture of a unidirectional composite under shock loading was estimated. The damping of oscillations of composite rings was described.

In [73], based on the averaging method, Annin et al. presented a method of determining the rigidity and strength characteristics of composites with a periodic structure. In [74], the inverse problem — determination of the structure of laminated and fibrous composites ensuring the prescribed mechanical characteristics — was discussed. Annin et al. [75] considered the problems of synthesis of a layered material with a periodic structure consisting of a large number of thin layers made of different materials and having the prescribed averaged elastic and thermophysical characteristics and also the problems of synthesis of elastic and thermoelastic multilayer structures of minimal weight.

Reznikov and Shalaginova [76, 77] proposed a technique for obtaining constitutive relations and for calculating the strength of lightweight fibrous composites based on the concept of structural analysis and on a rod-type mechanical model.

Many composite materials can be described within the framework of the anisotropic theory of elasticity. The mathematical structure of fourth-rank tensors of the elasticity moduli A_{ijkl} and of the compliance coefficients a_{ijkl} was studied by Ostrosablin [78–80]. The matrices of the elasticity moduli A and those of the compliance a are of the form $A = T\Lambda T'$, $a = A^{-1} = T\Lambda^{-1}T'$, $\Lambda = \mathrm{diag}\,(\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6)$, and $T' = T^{-1}$, while the canonical invariant writing of the generalized Hook's law is as follows:

$$\sigma_i t_{i1} = \lambda_1 \varepsilon_j t_{j1}, \quad \sigma_i t_{i2} = \lambda_2 \varepsilon_j t_{j2}, \quad \sigma_i t_{i3} = \lambda_3 \varepsilon_j t_{j3},$$

$$\sigma_i t_{i4} = \lambda_4 \varepsilon_j t_{j4}, \quad \sigma_i t_{i5} = \lambda_5 \varepsilon_j t_{j5}, \quad \sigma_i t_{i6} = \lambda_6 \varepsilon_j t_{j6}.$$

Here summation from 1 to 6 is performed over the repeat subscripts i and j; $T = [t_{ip}]$ and σ_i and ε_j are the stress- and strain-tensor components presented in the vector form

$$\sigma = (\sigma_{11}, \sigma_{22}, \sigma_{33}, \sqrt{2}\sigma_{23}, \sqrt{2}\sigma_{13}, \sqrt{2}\sigma_{12}), \qquad \varepsilon = (\varepsilon_{11}, \varepsilon_{22}, \varepsilon_{33}, \sqrt{2}\varepsilon_{23}, \sqrt{2}\varepsilon_{13}, \sqrt{2}\varepsilon_{12}).$$

The elastic eigenstates t_{ip}, which depend in the general case on 15 arbitrary parameters, were found using the orthogonalization and normalization of an arbitrary triangular matrix with diagonal elements equal to unity. The author classified anisotropic materials according to a number of different eigenmoduli λ_k and their multiples α_i. The symbol $\{\alpha_1, \alpha_2, \ldots, \alpha_k\}$, $k \leqslant 6$, $\alpha_i \geqslant 1$, $\alpha_1 + \alpha_2 + \ldots + \alpha_k = 6$ was put into correspondence with each material. All anisotropic materials were divided into 32 qualitatively different classes. The eigenmoduli of elasticity and the states for materials of crystallographic systems were found. In [78, 80], Ostrosablin solved the problem of the closest boundaries of elasticity constants, which was posed by Bekhterev in the 1920s, presented the necessary and sufficient conditions of positive definiteness of the specific deformation energy, and also gave formulas for practical elasticity constants showing the ranges of variability of these constants. Similar formulas were given for materials of all crystallographic systems. In [79], he found eigenvalues and eigenvectors for the tensor $A^*_{ijkl} = (A_{iklj} + A_{ilkj})/2$ of the coefficients in the equations of motion in terms of displacements of the linear theory of elasticity. Eigenvalues and eigenvectors were also found for matrices A^*_{ik} of the coefficients of materials of crystallographic systems. Based on the number of different eigenvalues and their multiples, he grouped the equations of motion into 32 classes and also indicated materials with negative Poisson ratios. It was noted that, in this case, the equations for each displacement become nondependent on each other.

3. Evolution of the Methods of Solving Problems in Mechanics of Solids [81–171]. (A) The symmetry properties were studied, and new exact solutions of various differential equations of the mechanics of solids were developed in [81–86]. In [81], Senashov and Vinogradov described all high-order local symmetries (Lie–Bäcklund group) and all conservation laws for equations of a Mises medium in a plane stationary case. These equations were shown to admit an infinite series of symmetries and conservation laws constructed by recurrent formulas. In [82], Senashov used these laws to derive a solution of the Cauchy problem in analytical form. In [83], he obtained new classes of solutions of the spatial equations of ideal plasticity describing helical-spiral flows, which can be used for analysis of the free state of rods under complex loading.

A wide range of problems of plane static and dynamic problems of the nonlinear theory of elasticity was investigated by the methods of the theory of complex-valued functions by Bondar' [87–90]. The method of reducing a two-dimensional plane problem to a one-dimensional boundary-value problem, which was developed in the linear theory, was extended to nonlinear elasticity, thus leading to nonlinear boundary-value problems for complex potentials. The latter was solved by a modified Newton method and by the method of small parameter. He considered the finite plane deformation under certain constraints (incompressibility and weak compressibility) and established sufficient ellipticity conditions for static equations. Radok's results in the linear theory were extended to a dynamic problem. A number of plane nonlinear problems, including the problems of an equistrength hole, the motion of pressure momentum over the surface of a semi-infinite elastic body, etc., were solved analytically.

The problems of the construction of general solutions of linear elasticity theory equations and also the problems of reduction of these equations to three independent wave equations were investigated in [91–95]. In [91, 92, 95], Ostrosablin found eigenoperators and eigenvectors for the system of differential equations of the linear theory of elasticity that allowed these equations to be reduced to three independent ones. He also derived formulas for an elastic anisotropic medium (generalization of the Green's medium) with purely longitudinal and transverse waves for any direction of the wave normal, as well as for special orthotropic and transversely isotropic materials [91, 92]. In [93, 95], Ostrosablin and Senashov showed that to each form of the general solution corresponds the formula of derivation of new solutions, i.e., a certain symmetry operator. The general solution of the linear system $Au = 0$ of partial differential equations of the elasticity theory is of the form $u = C\varphi$, $D\varphi = f$, and $Bf = 0$ or $u = C\varphi$ and $D\varphi = 0$ if D Ker $C =$ Ker B; note that $AC = BD$ [93]. The symmetry operator $Q = CB^*$ (the symbol $*$ refers to the formally conjugate operator, $A = A^*$, and $D = D^*$) transforms the solution of the equation $A\tilde{u} = 0$ into a new solution $u = CB^*\tilde{u}$ for $\varphi = B^*\tilde{u}$ as well. In the case of an isotropic material, Ostrosablin [93] found symmetry operators for the Kelvin–Lamé, Galerkin, and Papkovich–Neuber solutions and studied the generality of these solutions. It was shown in [94] that there are 17 equivalent forms with three compatibility conditions of small deformations. Seventeen forms of the general solutions of equilibrium equations via three stress functions and a correct formulation of the stress problem of the theory of elasticity were given.

Great attention was given to the method of studying elastic and elastoplastic problems based on the theory of variational inequalities. Khludnev [96–99, 126] proved the solvability of a wide range of elastoplastic boundary-value problems formulated with the use of variational inequalities. The problem of optimal control in Singorini-type contact problems for plates and shells was investigated in detail. In [100–103], Khludnev solved the problems of deformation of elastic and inelastic cracked bodies. At the crack faces, a boundary condition of mutual nonpenetration of the faces was found. For plates, this condition is of the form

$$[\mathbf{W}] \cdot \boldsymbol{\nu} \geqslant h \left| \left[\frac{\partial w}{\partial \nu} \right] \right|,$$

where $[\cdot]$ is the jump of the function at the crack faces, $2h$ is the thickness of the plate, $\mathbf{W} = (w^1, w^2)$, and w are the horizontal and vertical displacements of the plate, respectively, and $\boldsymbol{\nu}$ is the normal vector to the crack surface. He also found the complete set of natural boundary conditions in the form of a system of equalities and inequalities satisfied at the crack faces, and solvability of the boundary-value problems for cracked bodies was established. The proposed approach is different from the classical one, where the boundary conditions at the crack faces are of the form of equalities.

The investigations of Kovtunenko [104–108] were devoted to a numerical solution of variational inequalities. Differential inequalities were approximated by nonlinear differential equations with the use of the penalty method. He proposed iteration methods of their linearization, proved the convergence of the solutions of approximate problems, and estimated the errors. He also built linear approximate models for contact elastoplastic problems. Another promising approach to analysis of variational inequalities was the use of projection operators. Such projectors were constructed for a number of one-dimensional problems for the models of an elastic cut under the condition that the cut edges are not penetrable. This allowed him to reduce variational inequalities to differential equations and to solve them analytically. In addition, the problem of the choice of optimal cuts was studied based on the kinematic and force criteria.

Sadovskii and Annin [109–116] developed an approach based on the formulation of constitutive relations of the flow theory in the form of variational inequalities for hyperbolic operators. This approach advanced investigations along two lines: obtaining generalized solutions with velocity and stress discontinuities by elastoplastic shock waves and developing computational methods of solving dynamic problems. The following models of elastoplastic flow were studied: the Prandtl–Reis model of dynamic straining of an elastic-perfectly-plastic body and the Kadashevich–Novozhilov model of body strengthening with an arbitrary nonlinear hardening diagram. For the case of small elastoplastic deformations, integral generalizations of the models that allow one to define correctly the notion of discontinuous solutions were constructed. Shock waves in linearly hardening media under Mises and Tresca–St. Venant plasticity conditions were classified in [109–111]. In [112], based on variational inequalities, Sadovskii developed conservative numerical methods of solving the problems of deformation of elastic-perfectly-plastic bodies adapted to a through calculation of discontinuous solutions. Annin and Sadovskii [113] developed new economic algorithms for numerical solution of dynamic problems within the framework of a model of nonlinear isotropic and translational hardening including the correction of stresses and hardening parameters, with projection onto the yield surface. The proposed methods and algorithms were used in a numerical study of the processes of pulsed deformation of laminated plates on mandrels [114–116].

Algorithms for solving the problems of collision of deformable solids with allowance for material discontinuity caused by its fracture were developed and realized by Gulidov et al. [117–119]. Numerical algorithms for solving the dynamic problems of elastic and plastic deformation on the basis of several independent approximations of desired functions were reported by Anisimov and Bogulskii [120]. On each layer, two- and three-dimensional problems were split in time into one-dimensional with a simultaneous formation of artificial dissociation which is sufficient for ensuring the monotone character of the numerical solution. In [121], Mashukov developed the ELAST code intended for solution of plane and spatial problems of the linear elasticity theory and also solved a number of problems for a curvilinear ponderable half-plane by realizing numerically the method of singular boundary integral equations.

As applied to the solution of thermoelastoplastic problems, the finite-element method was developed in [122–131]. In [122], Korobeinikov et al. described the possibilities of the PIONER program intended for solution of geometric and material nonlinear static and dynamic problems of the mechanics of solids. Use was made of various models for materials: the model of linear isotropic elastic material, the Mooney–Rivlin incompressible hyperelastic material model, the model of thermoelastoplastic material with allowance for creep deformation, and the model of linear elastic material with allowance for fracturing. The solutions of some plane and axisymmetric nonlinear problems obtained by means of this complex were given by Korobeinikov [123, 124]. The temperature effect on the critical time of creep buckling of a hinged axially compressed rod was studied by Annin et al. [125]. Algorithms for solving nonlinear contact problems were proposed in [126, pp. 167–177; 127, 128]. These algorithms were applied in the development of two- and three-dimensional contact elements. The PIONER program allowed one to solve contact problems by two alternative methods: the method of Lagrange multipliers and the penalty-function method. The three-dimensional geometric and material nonlinear contact problem was solved by Korobeinikov, Alekhin, and Bondarenko [128]. A new finite element intended for the solution of problems of deformation of thin-walled structures was given by Korobeinikov and Bondarenko [129, 130]. A new approach to the formulation of the element was the introduction of a tangential stiffness matrix due to large rotation increments, and the use of nodes with five or six degrees of freedom in one element, which makes it possible to simulate complicated thin-walled structures. In [130], a problem that simulates the formation of a curvilinear panel from a reinforced aluminum plate was solved. In [131], Korobeinikov constructed a finite element of the atomic lattice (atomic pair) by means of which one can solve the problems of deformation and buckling of atomic lattices subjected to mechanical actions. A new model of monocrystal fracture was proposed based on the solution of the problem of tension of a four-atomic cell.

Algorithms for solving static and dynamic problems of the theory of elasticity and plasticity were developed by Volchkov et al. [132–134]. In [133], an iteration method of solving static problems was proposed based on the transformation of the residuals of equations into self-balanced ones and on a subsequent extension of the self-balance region of residuals. The method was shown to be efficient by solving problems for the Poisson equation with strongly varying coefficients. Volchkov et al. [134] constructed the finite element upon conjugation between the elements as the condition of force and moment continuity at the element faces.

A discrete-variational method of constructing models for computer simulation of nonlinear dynamic processes of deformation and fracture of homogeneous and composite materials and structural members was proposed by Koshur et al. [135, 136]. A computational algorithm for simulation of two- and three-dimensional dynamic contact interactions of bodies being deformed was developed with allowance for elastoviscoplastic deformation and fracture of materials.

In [133–138], the solutions of continuum mechanics equations for which deformations are uniform were discussed. In [140, 141], Bogan investigated problems of the anisotropic theory of elasticity with a small parameter. A semi-analytical method of solving dynamic problems of wave propagation in thin-layered media (the thickness is smaller than the wavelength) was proposed by Nazarov in [143]. In [144], he proposed a modification of the integration method which allows one to solve mixed dynamic problems and presented examples of the action of a vibration source on the surface of an elastic half-space and of wave propagation in a medium with a boundary along which the contact is not complete.

The investigations in [145–153] dealt with the correctness of inverse static problems and with the development of algorithms for their solution. Among those considered were

• inverse problems of inelastic deformation which are associated with the determination of external actions necessary to obtain the required residual shape of a body for a given period with allowance for elastic (instantaneous) and inelastic (slow) unloading upon removal of these deformations [145–147];

• problems in which displacements and loads are prescribed simultaneously on a definite section of the surface of a loaded body and are not determined on the remaining section of the body [148–151];

• essentially overdetermined problems in which the displacement and the load are given simultaneously over the entire surface of a body, and it is necessary to determine the body's average characteristics and to find inhomogeneities in it (cracks, hollows, and inclusions) [152, 153].

The effect of the shape of a pulse load on the residual sagging of plates whose boundaries consist of straight sections and circular arcs was studied with the use of a rigid-plastic model by Nemirovskii and Romanova [154].

The problem of fracture of an elastoplastic plate by a penetrating rigid striker was solved by Babakov and Zinov'ev [155]. Taking into account the crack zone moving ahead of a striker allowed them to describe the effect of back spalling of the plate. Results of a study of back spalling of the plate in impact against its face surface by a sharpened rigid striker were reported. Plate materials were described by an elastoplastic model with yield cutoff. In penetrating a striker, three deformation zones were assumed to appear in an obstacle: a plastic-deformation zone, a crack zone, and an elastic-deformation zone. They also revealed that taking into account the cracks formed during piercing of a plate gives rise to a scale effect — the effect of the dimensions of a striker and a plate on the critical depth of striker penetration at which spalling of the rear surface of the plate begins.

(B) One method of constructing two-dimensional equations of the theory of plates and shells is thickness expansion with the use of Legendre polynomials, on the basis of which G. V. Ivanov developed a technique of using several approximations of the same unknown functions as the sections of the series in Legendre polynomials. Based on this technique, Alekseev [156] obtained a one-parameter family of successive approximations of equations of deformation of a variable-thickness layer in an arbitrary curvilinear coordinate system. In [157], he described a procedure of reducing three-dimensional equations of the linear theory of elasticity to a two-parameter sequence of two-dimensional problems of a variable-thickness elastic layer in an arbitrary curvilinear coordinate system. In specifying various variants of the boundary conditions on face surfaces, the differential order of the equations for each approximation does not change: stresses, displacements, and combined conditions can be given.

Nonlinear models of deformation of shells and rods with six and nine kinematic degrees of freedom, respectively, were constructed by Shkutin [158]. In [142], he derived nonlinear equations of shell and rod deflection with allowance for the finite rotation of material elements. For this purpose, he introduced force and deformation tensors which are not sensitive to rigid rotations and are energetically conjugate in the metrics of a rotating basis.

The application of a numerical-analytical approach to the solution of nonlinear buckling problems for thin-walled shells enabled Astapov and Kornev to describe the process of shell buckling [159, 160]. They found that in finite saggings, the initial section of the spectra of critical loads is distorted, the buckling shapes rearrange, and local buckles can appear. They considered models describing the supercritical behavior of a hinged rod lying on a nonlinear-elastic base and loaded by an axial compressing force. Analytical expressions for buckling shapes and for the load–sagging dependences were obtained by the perturbation method. The initial supercritical behavior of the system relative to the values of parameters characterizing the rigidity of a base were analyzed. The possibility of unstable supercritical behavior of the system was predicted analytically and shown experimentally. Contradictions that appear in using some known models of an elastic base for description of rod buckling were clarified.

(C) The problem of rational design of shells was dealt with by Nemirovskii and Samsonov [54] and by Golushko et al. [161–165]. The momentumless character of the stress state, the equal stress level over the reinforcement, the constancy of the specific potential energy, etc. served as the rationality criteria. The governing parameters were material structure, shell shape, and wall thickness. The problem of determining the shape, dimensions, and parameters of the structure of a shell of revolution from a fibrous composite at which the shell has a given sagging was studied. The load on the shell was assumed to be known. In [162], Golushko and Nemirovskii used the condition of the equal stress level of reinforcing elements at the outer or inner surface of a shell as the rationality criterion. In [164], Mezentsev and Nemirovskii studied rational structures of reinforcement of polyreinforced shells.

The methods for calculating and designing optimal-in-durability structure elements with simultaneous allowance for the vulnerability to damage of the material during its creep were developed by Zaev and Nikitenko [166, 167]. The papers by Alekhin and Baev [62], Alekhin et al. [75], Babe and Gusev [168], Kanibolotskii and Urzhumtsev [169], and Alekhin and Annin [170, 171] were devoted to the development of methods of solving the problems of optimal design of laminated structures from a given limited set of materials.

4. Fracture Mechanics [172–192]. A wide class of problems of finding the shapes of crack trajectories in an elastobrittle medium in hydraulic rupture, impact, and in "weak" explosion were solved in [172–180]. In the step-by-step construction of the quasi-static trajectory, the damage criterion according to which the crack moves in the direction orthogonal to the action of maximum tensile stresses in the vicinity of its tip at each moment of crack propagation was used. In [172], Kolodko and Martynyuk studied the specific features of the coalescence of two cracks depending on their orientation in the biaxial field of tensile stresses. Trajectories of the crack tips in hydraulic rupture near the plane free boundary and the bench were found by Alekseeva and Martynyuk [173]. In [174], Martynyuk and Sher [174] showed the decisive effect of the parameters of an external biaxial field of compressive stresses near the hole and of the hole field on the shape of the hydraulic-rupture crack trajectory when the pressure in it is comparable with stresses acting at infinity. In [175], Efimov et al. compared the calculated trajectories of cracks formed during shearing of a bench with experimental ones and also showed their good agreement despite high velocities of cracks (approximately 250 m/sec). In [176, 177], Basheev, Martynyuk, and Sher analyzed the shapes of the trajectories of the cracks originating from the boundary of an explosion well, with variation in the basic parameters of an explosion and of the external biaxial field of compressive stresses acting at infinity. They showed that the fracturing zone is close in shape to an ellipse whose principal axis is oriented in the direction of the largest (in modulus) external compressive stress. The effect of gas penetration into the systems of cracks on the shape and dimensions of the fracture zone was evaluated. A simple technique of determining the resistance of rock-type brittle materials to cracks was substantiated theoretically and experimentally by Efimov et al. [178–180].

Overloads on the surface of an isotropic or piecewise-isotropic half-space with the arrival of waves generated by the internal defect like a crack growing from a point along a curve at an angle to the surface were studied by Saraikin [181–183]. An analytical solution was obtained for the initial stage.

The discrete Novozhilov criterion of brittle strength of an ideal crystalline solid for a crystalline lattice with defects (vacancies, admixture atoms, etc.) was generalized by Kornev in [184–189]. For opening-, tearing- and sliding-mode cracks, discrete-integral criteria of brittle strength were introduced. In the modified Novozhilov criterion, the limits of stress averaging depend on the presence of a defect in the crystalline lattice and on its dimension and location in the vicinity of the crack nose. The magnitude of the averaged stresses should not exceed theoretical rupture and shear strengths. The substantial effect of vacancy-type defects on the critical crack lengths in the vicinity of the crack nose under various types of loading were revealed. According to the discrete criterion for an ideal cracked crystalline solid and the discrete-integral criterion for bodies with vacancies in the crystalline lattice, the critical lengths of opening-mode cracks are usually different by an order of magnitude. According to the Novozhilov and discrete-integral criteria, the critical values of loads for fixed crack lengths are severalfold different and give maximum and minimum estimates for failure loads of solids. According to the discrete-integral criterion, the critical load can differ substantially from the classical one, and its value is directly connected with the defectiveness of the lattice of a crystalline solid in the vicinity of the crack nose. Relations for the critical stress intensity factor of both sharp and blunt (at the atomic level) opening-, tearing-, or sliding-mode cracks were derived by means of discrete-integral criteria. The stability of the broken front of a plane crack was discussed, and the broken crack front was shown to tend to a rectilinear one.

The formulated strength criteria allowed one to evaluate the effect of surface-active substances in the crack on the strength of crystalline solids: homoabsorbing atoms on the newly formed crack surface suppress the forces of interatomic interaction inside the crack. The tension of three- and four-atomic chains with admixture atoms was considered at a given level of tension. These atomic chains were built in an infinite chain of bound atoms stretched at infinity. Admixture atoms could be either bound or free. As the potential of interatomic interaction, the Morse potential was used. A set of three imaginary positive dimensionless quantities, the first two of which reflect the effect of the energy factor and the third of which reflects the effect of the dimensional factor, was introduced. The level of strength decrease reached one or two orders of magnitude. The decrease in the rupture strength of the atomic chain with the admixture if the latter was located at the crack tip could sharply decrease the local resistance to fracture and lead to crack propagation under loads that are considerably smaller than the theoretical strength of an admixture-free material.

In [190–192], Annin, Maximenko, and Abramenko determined the stress intensity factors in composite plates and shells.

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